

Mercury-Ion-Trap Clock

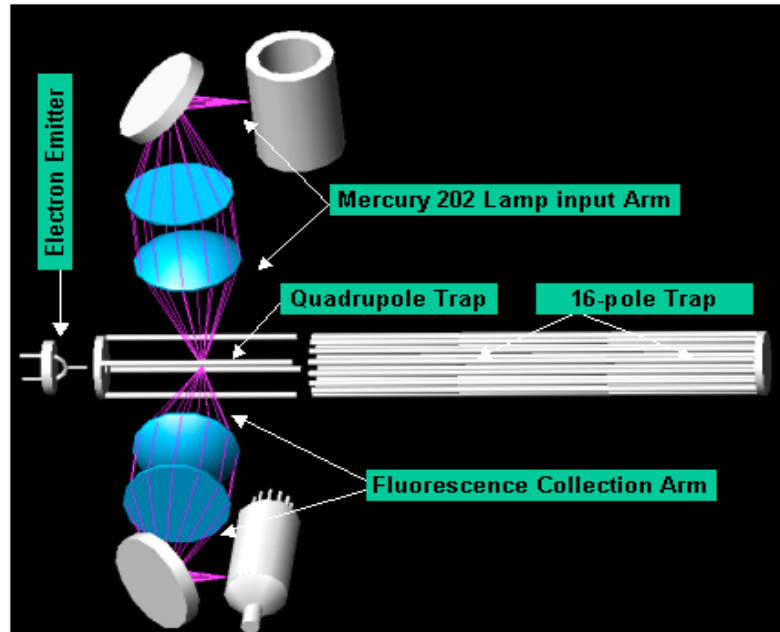
This clock technology is based on $^{199}\text{Hg}^+$ ions trapped in a linear rf ion trap developed at JPL specifically for ultra-stable space-clock operation. Ion-trap-based Hg clocks offer many advantages over other high-performance clock technologies being developed today. The inherent magnetic sensitivity of Hg^+ is the lowest of all the microwave-clock atoms and the temperature sensitivity of the unregulated clock package is far smaller than any other atomic clock.

To be small and reliable, the ion-clock technology, by design, does not use lasers, cryogenics or microwave cavities. Traditional ion-trapping methods have been extended to include ion shuttling, taking full advantage of the ion's charge. This method was invented at JPL specifically to make small, practical, ultra-stable clocks. Ion trapping effectively eliminates frequency pulling from wall collisions inherent to gas-cell clocks. Ion shuttling allows separation of the state selection process from the clock microwave-resonance process so that each can be independently optimized for its task.

This separation of functions is taken for granted in atomic-beam clocks, but has proven to be a powerful tool with charged ions since the “beam” of charged ions can be reversed in direction and halted, and can propagate with no loss of atomic particles. Two ion-trap regions are employed, a quadrupole linear trap where ions are tightly confined where optical state selection from a ^{202}Hg rf discharge lamp is carried out, and a higher pole trap where ions are more loosely confined and microwave clock transitions are executed.

The higher pole trap used for microwave clock interrogations creates less rf ion motion in the trapping fields than experienced in a quadrupole rf trap. Because ion heating caused by the rf trapping fields leads to frequency instabilities, its reduction in the multipole trap is a simple method to provide very good long-term clock stability. This architecture has been implemented in a small vacuum tube (~ 1 liter) because charged ions are readily transported back and forth between the two trap regions.

Ions are not laser-cooled so that a very small and simple clock package can be engineered. At room temperature, the ion fractional frequency shift due to thermal motion and the consequent time dilation of moving clocks is about 3×10^{-13} . That is, if the ions are cooled from room temperature to near absolute zero, their clock frequency will shift by 3×10^{-13} in the process. Proportionately, if ions change temperature by 1 degree C, the clock will change output only by 1×10^{-15} . This is by all clock standards a very small temperature sensitivity, and it is a practical task to regulate the temperature of the vacuum tube holding the ion-trap to much less than 1 degree C. For this reason and others, Hg ion clocks, small enough to travel into deep space where ultra-low mass is required, are being developed at JPL.



The elements of the ion clock. Ions are generated by an electron pulse injected into the quadrupole trap, ionizing a dilute vapor of ^{199}Hg . Fluorescence from the trapped ions is generated by the 194-nm UV light from the ^{202}Hg lamp, optically pumping the ions into the lower clock state where fluorescence ceases. Ions are then electrically shuttled into the 16-pole trap where the ion density falls, rf motion from the trapping fields is greatly reduced, and magnetic fields from external sources are shielded away. Microwaves applied at 40.507348 GHz will repopulate the upper clock level when tuned to within ~ 100 milli-Hz of the ion-clock transition frequency. Following this clock interrogation, ions are shuttled back into the quadrupole trap where transitions to the fluorescing upper clock state are detected.